

Magnetoelectric bistabilities in ferromagnetic resonant tunneling structures

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The conditions for the occurrence of pronounced magnetoelectric bistabilities in the resonant tunneling through a ferromagnetic quantum well are theoretically investigated. The bistability appears due to the mutual feedback of the carriers Coulomb interaction and the carriers exchange coupling with magnetic impurities in the well. It is shown that the well Curie temperature depends strongly on the relative alignment of the quantum well level and the reservoirs chemical potentials, which can be modified electrically. Switching between a "current-on/magnetism-off" and a "current-off/magnetism-on" mode becomes possible, if the well temperature lies in-between the bistable values of the well Curie temperature.

In ultimate magnetoelectric devices the magnetic properties should be ideally controllable to a vast extent by external bias or gate fields. For this purpose, band-engineered magnetic resonant tunneling structures are very promising, since they exhibit a rich variety of tunable magneto-transport properties [1]. Especially, the impetuous development of novel dilute magnetic semiconductors (DMSs) [2, 3, 4] in the last decades, which are made magnetic by randomly doping with transition metal elements, e.g., by incorporating Mn in a GaAs crystal host, has considerably enriched the possibilities of growing different magnetic semiconductor heterostructure systems. In DMSs the ferromagnetism can depend strongly on the actual particle density, which has been confirmed in several experiments, in which ferromagnetism has been generated by tailoring the particle density by electrical or optical means [5, 6].

In magnetic resonant tunneling structures made of para- or ferromagnetic DMSs even small energetic spin splittings of the well subbands can become observable in the transport characteristics [7, 8, 9]. Based on their spin-dependent transmission magnetic resonant tunneling structures have been proposed for realizing efficient spin valves and spin filtering devices [1, 10], or for digital magnetoresistance [11, 12]. The magnetic properties of ferromagnetic quantum wells made of DMSs are well described in the framework of a mean field model [13, 14, 15, 16], which reveals that the Curie temperature of the well depends on (i) the 2D-spin susceptibility of the carriers and (ii) on the overlap of the subband wave function with the magnetic impurity density profile. Both parameters should be in principle tuneable by the applied bias, which would provide a purely *electrical* control of the ferromagnetism in magnetic quantum wells.

In conventional nonmagnetic resonant tunneling diodes (RTDs) it is well known, that an intrinsic hysteresis in the negative-differential-resistance (NDR) region of the current-voltage (IV) characteristics can occur [17]. This

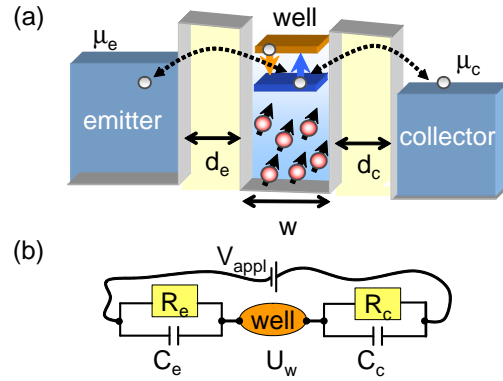


FIG. 1: (Color online) (a) Schematic scheme of the band profile of the magnetic double barrier structure. The exchange interaction of the magnetic ions is mediated by the carriers tunneling in and out of the well. (b) Equivalent circuit model of the resonant tunneling structure introducing the emitter and collector capacitances C_e, C_c and resistances R_e, R_c , respectively.

bistability of the tunneling current has been explained to result from the nonlinear feedback of Coulomb interaction of the stored well charge [18, 19]. In magnetic RTDs this naturally suggests the possibility of hysteretic magnetic states, as has been predicted in [20, 21].

In this article a detailed study of possible magnetoelectric bistabilities in magnetic RTDs is provided. The carriers dynamics is described by a self-consistent sequential tunneling model, which includes the feedback effects of both the carriers Coulomb interaction and the magnetic exchange coupling with the magnetic ions. The model yields a simple expression for the steady state 2D-spin susceptibility, which allows to calculate the critical temperature T_c of the quantum well depending on the applied bias and the relative alignment of the quantum well level with respect to the chemical potentials of the emitter and collector reservoirs. If the well is operated at a temperature, which lies between the bistable values of the well Curie temperature, the magnetic RTD can be switched between a "current-on/magnetism-off" and a "current-off/magnetism-on" mode.

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The band profile of a generic double-barrier resonant tunneling structure with a ferromagnetic quantum well made of a DMS, e.g., of GaMnAs, is sketched in Fig. 1(a). The vertical transport through the structure can be described by a sequential tunneling model, since the high density of magnetic impurities in the well will likely cause decoherence processes. By using the transfer Hamiltonian formalism a Pauli master equation for the statistical distribution of the particles in the well can be derived [1, 22]. In the case that only a single resonant level E_w resides in the energy window of interest, which is defined by the difference of the emitter's and collector's chemical potentials, simple rate equations for the spin-resolved well particle densities $N_\sigma(t)$ with $(\sigma = \uparrow, \downarrow)$ are obtained

$$\frac{dN_\sigma}{dt} = \Gamma_e(E_\sigma) N_{e,\sigma} + \Gamma_c(E_\sigma) N_{c,\sigma} - \Gamma(E_\sigma) N_\sigma. \quad (1)$$

Here, $N_{\sigma,\{e,c\}}$ are the densities of particles with the resonant longitudinal energy E_σ in the emitter (e) and collector (c) reservoir, respectively. The energy-dependent tunneling rates $\Gamma_{\{e,c\}}$, $\Gamma = \Gamma_e + \Gamma_c$ can be calculated by Bardeen's formula [23], which essentially evaluates the overlap of the lead and well wave functions in the barriers. For high barriers these tunneling rates become proportional to the longitudinal momentum p_z of the incident particles [22], i.e., $\Gamma_{e,c} \propto (E_z)^{1/2}$ with E_z denoting the longitudinal energy. By assuming that the particle reservoirs are described by Fermi-Dirac distributions the particle densities are given by $N_{i,\sigma} = D_0 k_B T \ln \{1 + \exp[(\mu_i - E_\sigma)/k_B T]\}$, $i = (e, c)$, with $D_0 = m/2\pi\hbar^2$ is the two-dimensional density of states per spin for carriers with the effective mass m , k_B denotes Boltzmann's constant, T is the lead temperature, and μ_i are the emitter and collector chemical potentials with $\mu_c = \mu_e - eV_{\text{appl}}$ where V_{appl} is the applied bias.

In the framework of a mean field model an analytic expression for the steady state exchange splitting Δ of the well level can be derived [1, 13, 15, 16]

$$\Delta = J_{\text{pd}} \int dz n_{\text{imp}}(z) |\psi_0(z)|^2 \times S B_S \left[\frac{S J_{\text{pd}} s (N_\downarrow - N_\uparrow) |\psi_0(z)|^2}{k_B T} \right], \quad (2)$$

where J_{pd} is the coupling strength between the impurity spin and the carrier spin density (in case of GaMnAs p-like holes couple to the d-like impurity electrons), z is the longitudinal (growth) direction of the structure, $n_{\text{imp}}(z)$ is the impurity density profile, $\psi_0(z)$ labels the well wave function, and $s = 1/2$ is the particles spin. The Brillouin function of order S is denoted by B_S , where S is the impurity spin, which for Mn equals 5/2. By considering a homogenous impurity distribution Δ is effectively determined by the voltage dependent spin polarization $\xi = s(N_\uparrow - N_\downarrow)$.

The nonlinear feedback of the Coulomb interaction of the well charges is approximately taken into account by calculating the electrostatic well potential in terms of

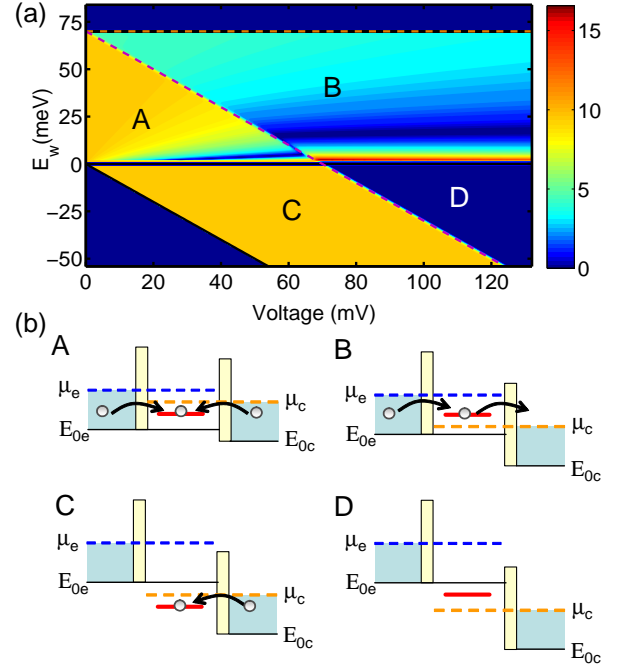


FIG. 2: (Color online) (a) Contour plot of the well Curie temperature T_c (K) as a function of the well level position E_w and the applied bias. (b) Schematic illustration of the different occupation probabilities of the quantum well level from the reservoirs for the regions A-D, as indicated in the contour plot (a). The emitter and collector band edges are denoted by E_{0e} and E_{0c} , respectively.

an equivalent circuit model of the resonant tunneling diode, as shown in Fig. 1(b), where the capacitances C_e and C_c are determined by the geometrical dimensions of the barriers and the well [22]. The potential results in $U_w = [e^2(N - N_{\text{back}}) - C_c e V_{\text{appl}}]/C$, where $N = N_\uparrow + N_\downarrow$, $C = C_e + C_c$, e denotes the elementary charge, and N_{back} is the positive background charge in the well, which originates from the magnetic donors. Since the actual position of the quantum well levels $E_\sigma = E_0 + U_w - \sigma\Delta$ depends on both the magnetic exchange splitting Δ and the electrostatic potential U_w all equations become nonlinearly coupled, making a selfconsistent numerical solution necessary.

In order to find criterions for the occurrence of magnetic bistabilities and to interpret the numerical results in the following it is very useful to study the dependence of the well Curie temperature T_c on the applied bias and the well level position. The mean field model yields an analytic expression for the collective Curie temperature of a magnetic quantum well

$$k_B T_c = \frac{S(S+1)}{3} J_{\text{pd}}^2 \chi_{2D} \int dz n_i(z) |\psi(z)|^4, \quad (3)$$

where the two-dimensional spin susceptibility is defined

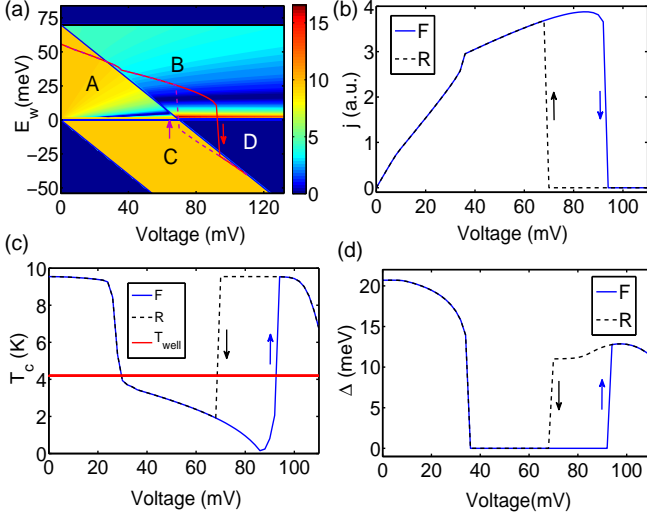


FIG. 3: (Color online) The (a) quantum well level position E_w , (b) current j , (c) Curie temperature T_c , and (d) well splitting Δ as a function of the applied bias. The solid lines indicate the voltage up-sweep values (F), whereas the dashed lines correspond to the voltage down-sweep values (R). In (a) the E_w -voltage curves are embedded in the contour plot of the well Curie temperature T_c (K) and in (d) the solid red line corresponds to the actual well temperature $T_{\text{well}} = 4.2$ K.

by

$$\chi_{2D} = \lim_{\Delta \rightarrow 0} \frac{s(N_{\uparrow} - N_{\downarrow})}{E_{\downarrow} - E_{\uparrow}}. \quad (4)$$

Within the introduced sequential tunneling model Eq. (1) the steady state spin susceptibility simplifies to $\chi_{2D}(E) = -s(\partial N_0 / \partial E)$, where $N_0 = (\Gamma_e N_e + \Gamma_c N_c) / \Gamma$ is the steady state solution of the rate equations (1). Hence, the dimensionless susceptibility can be written as

$$\tilde{\chi} = \frac{\chi_{2D}(E)}{sD_0} = \sum_{i=e,c} \frac{\Gamma_i}{\Gamma} f_{\text{FD}}^i - \frac{N_i}{D_0} \frac{\partial}{\partial E} \left(\frac{\Gamma_i}{\Gamma} \right) \quad (5)$$

with $f_{\text{FD}}^i, i = (e, c)$ denoting the Fermi-Dirac function for the emitter and collector reservoir, respectively. This allows to calculate the Curie temperature T_c as a function of the applied voltage (note that T_c depends via f_{FD}^c explicitly on the voltage, since $\mu_c = \mu_e - eV_{\text{appl}}$) and the well level position, as displayed in Fig. 2(a). For the simulations I used generic parameters corresponding to a GaMnAs well: $m = 0.5 m_0$, $\epsilon_r = 12.9$, $d_e = d_c = 20$ Å, $w = 10$ Å, $\mu_e = 70$ meV, $n_{\text{imp}} = 1.5 \times 10^{20} \text{cm}^{-3}$, $J_{\text{pd}} = 0.06$ eV nm³, where d_e, d_c and w are the emitter barrier, collector barrier and quantum well widths, m_0 denotes the free electron mass, and ϵ_r is the relative permittivity of the well. The background charge $n_{\text{back}} = 0.1 n_{\text{imp}}$ is considered to be only of about 10% of the nominal Mn doping density [24] and the lattice temperature is set to $T = 4.2$ K.

The Curie temperature contour plot can be divided into four qualitatively different regions A-D, which are

characterized by different probabilities for occupying the quantum well level from the reservoirs, as schematically illustrated in Fig. 2(b). In region A, for instance, the well level can be occupied by particles originating from both reservoirs. The Curie temperatures $T_c^{(A,C)}$ in regions A and C differ roughly by a factor 2 compared to T_c^B of region B. This sudden change of T_c can be explained as follows: by assuming energy-independent tunneling rates and nearly symmetric barriers, i.e., $\Gamma_e \approx \Gamma_c$ the dimensionless spin susceptibility of Eq. (5) simplifies for region A to $\tilde{\chi}^A = 1/2(f_{\text{FD}}^e + f_{\text{FD}}^c) \approx 1$, whereas in the other regions one obtains: $\tilde{\chi}^B = f_{\text{FD}}^e/2 \approx 1/2$, $\tilde{\chi}^C = f_{\text{FD}}^c \approx 1$, and $\tilde{\chi}^D = 0$. This simple estimation, hence, yields the desired result $T_c^{(A,C)} / T_c^B \approx 2$.

These differences in the Curie-temperatures of the various regions can now be exploited to realize hysteretic magnetoelectric states. According to the nonlinear feedback of the stored well charge, the resonant level E_w and the IV-characteristic show a hysteretic behavior, as displayed in Fig. 3(a) and (b). For the up-sweep (F) of the applied bias the well is charged before the E_w becomes off-resonant, i.e., when it drops below the emitter band edge, whereas for the voltage down-sweep (R) the well is almost uncharged before E_w becomes resonant again. This leads to different self-consistent electrostatic potentials for up- and down-sweeping voltages, explaining the occurrence of the intrinsic bistability. If the hysteresis of E_w now switches exactly between the T_c -regions B and C, as it is the case in Fig. 3(a), then also the voltage-dependent Curie temperature will exhibit a pronounced hysteresis, as shown in Fig. 3(c). The electric hysteresis will then be accompanied by a magnetic hysteresis if the actual lattice temperature T of the quantum well, which is displayed as straight solid line in Fig. 3(c), fulfills the condition $T_c^B < T < T_c^C$. This is illustrated in Fig. 3(d): as long as the resonant level stays in region B the well is nonmagnetic ($\Delta = 0$, since $T > T_c^B$) but when E_w enters the region C the well becomes immediately magnetic ($\Delta \neq 0$). Also notice, that at low voltages the well is always magnetic. At roughly $V_{\text{appl}} \approx 30$ mV the well becomes nonmagnetic, since E_w crosses the boundary between the regions A and B, which provides a purely electrical control of the well magnetism. As a whole, the magnetic well switches between a "current-on/magnetism-off" state for the up-sweep and a "current-off/magnetism-on" state for the down-sweep of the applied voltage. Moreover, the T_c contour plot in Fig. 2(a) also suggest the possibility for realizing the switching between a "current-on/magnetism-on" and a "current-off/magnetism-off" mode in the case that the hysteresis of E_w switches between region B and D and if $0 < T < T_c^B$.

In summary, I have shown by using a selfconsistent sequential tunneling model that the Curie temperature of a magnetic quantum wells strongly depends on the relative alignment of the well level and the reservoirs chemical potentials, which can be modified by external bias or gate fields. Magnetoelectric bistabilities become possible

if the hysteresis of the well level position E_w switches between regions of different well Curie temperatures and if the actual well temperature lies in-between these two values.

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